ECHOLOCATION RECOGNITION OF DIFFERENT WALL TEXTURES

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Abstract
This article investigates to what extent people are able to distinguish differences in wall textures by listening to the reflection of a click sound. Various wall morphologies and sound pressure signals were simulated using a 2D finite difference method for 12 different surface textures, for walls placed at 1.5m and 10m from the source/listening position. Listening tests show that the effect on the reflected sound of a staircase shape and a concave parabolic shape is noticeable, especially at 10m distance.

Keywords: Echolocation, Finite Differences

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1 Introduction

Though at first sight, contrary to multidimensional visual information (2D stereovision + 1D colour spectrum + motion) audio information seems limited (1D stereo), looking a bit closer into auditory cues, binaural audio signals are extraordinarily rich in information as well, thanks to the streaming spectral information (with a much higher frequency bandwidth than visual cues), and to the additional information in the modulation. This aspect becomes clear when looking at the great variability in stereo spectrograms of sounds.
By exploiting this, many blind people are able to recognize features of their environment by listening to a self-made click or hiss sound reflected off surfaces in their surroundings. Some of them are even trained in such a way that they are able to fully recognize objects around them so that they can navigate themselves very well without the need for probing the space by touching. They are able to do this by interpreting the time of arrival, strength and spectrum of the reflections of self-made impulsive sound, or the coloration of the spectrum in cases where the echo and direct self-made sound of longer duration overlap and interfere [1].

In this work we elaborate further on this line of work by verifying to what extent it is possible to not only recognize the presence of reflecting walls, but to also be able to distinguish between walls with different surface textures. We have tackled the problem by simulating acoustic environments and sound pressure signals using a 2D finite difference (FD) method, for 12 different wall surface textures at a distance of 1.5m and 10m with respect to a source.

For the sake of simplicity, we have modeled spherically symmetric Gaussian source mimicking the mouth of a person making a click sound, and a point receiver in the vicinity of the source, mimicking the ear of the same person listening to the self-made click and the subsequent echoes.

In the following, the main aspects of the FD calculation and the convolution between the source-receiver impulse response and a recorded real life click stimulus are summarized, the objective features of the impulse responses are discussed, and the results of listening tests, in which people tried to detect auditory differences due to differences in wall surface texture between pairwise presented sound stimuli, are presented.

2 Finite Difference calculation details

The simulation of acoustic environments and signals was done using a 2D finite difference method implemented in Matlab. A calculation domain including the point source, the point detection location of interest, and the wall was divided into square grid elements, whose size $\Delta x=\Delta y=2.67$mm was taken slightly smaller than the sound propagation distance $\Delta s=c\Delta t$, with c=343m/s the speed of sound in air, during a discrete calculation time step $\Delta t=1/f_s$, with sampling frequency $f_s=192$kHz. The Gaussian source was introduced with its center in the middle of the calculation domain (position (x_s, y_s)) via a t=0 starting condition:

$$p(x,y,t=0) = e^{-\left(\frac{x-x_S}{w}\right)^2-\left(\frac{y-y_S}{w}\right)^2} \tag{1}$$

The source radius w=2.8cm was chosen to be of the order of the mouth opening, and to generate frequencies up to about c/w=13kHz, covering the bandwidth that is most relevant for speech. The initial condition for the velocity was

$$v(x,y,t=0)=0 \tag{2}$$

The calculation then proceeded by implementing stepwise sequential updates of the velocity and pressure field according to the Euler equations:

$$v_{x,new}(x,y)=v_{x,old}-\frac{1}{\rho_0}\frac{\Delta p}{\Delta x}\Delta t \qquad v_{y,new}(x,y)=v_{y,old}-\frac{1}{\rho_0}\frac{\Delta p}{\Delta y}\Delta t$$
$$p_{new}(x,y)=p_{old}(x,y)-c^2\rho_0\left[\frac{\Delta v_x}{\Delta x}+\frac{\Delta v_y}{\Delta y}\right]\Delta t \tag{3}$$

with $\rho_0=1.3$kg/m^3 the static density of air, and

$$\frac{\Delta p}{\Delta x}=\frac{p_{old}(x+\Delta x,y)-p_{old}(x-\Delta x,y)}{2\Delta x}\ ;\ \frac{\Delta p}{\Delta y}=\frac{p_{old}(x,y+\Delta y)-p_{old}(x,y-\Delta y)}{2\Delta y}$$

$$\frac{\Delta v_x}{\Delta x}=\frac{v_{x,old}(x+\Delta x,y)-v_{x,old}(x-\Delta x,y)}{2\Delta x} \tag{4}$$

$$\frac{\Delta v_y}{\Delta y} = \frac{v_{y,old}(x, y+\Delta y) - v_{y,old}(x, y-\Delta y)}{2\Delta y}$$

The presence of the (perfectly rigid) wall was implemented by forcing the velocity component perpendicular to the (staircase-element-sequence-approximated) wall surface to zero. Also the boundaries of the calculation domain were assumed to be perfectly rigid. Snapshots of the wave pressure field after 850 timesteps are shown in Figure 1 for reflections off walls with different surface morphologies. The 3D pressure field evolution is substantially influenced by the morphology of the reflecting wall.

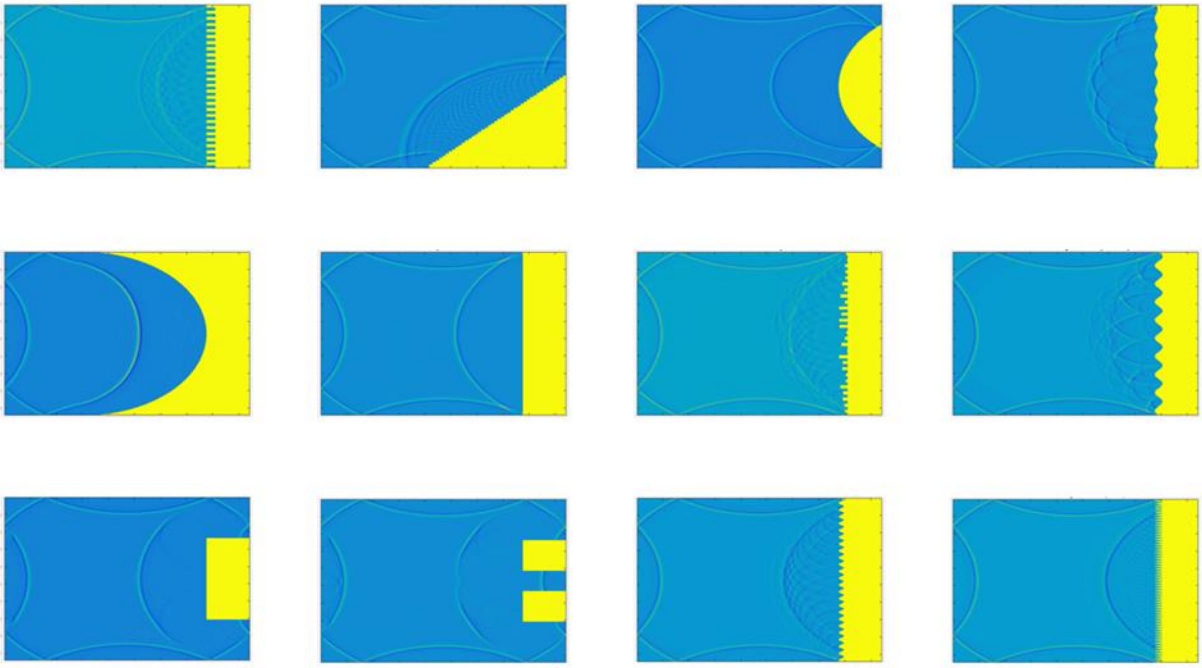

Figure 1. Plots of simulated pressure fields excited by a Gaussian source (radius 2.8cm) in the middle of a rectangular calculation domain with rigid edges, for walls with different surface morphologies on the right, after 850 time steps. The distance between the source and the object is 150cm.

3 Spectral and temporal features

In order to gain understanding to what extent the wall echo wavefront distortion induced by corrugated or other non-flat wall textures are audible, in the following, we look into the spectra of the wall echo alone, and the wall echo mixed with the direct sound. The former is relevant for situations in which the echo and the direct sound and temporally separated, as in the case of a faraway wall and a short stimulus. This is the case in the presented results (source width 5.6cm much smaller than source-wall-detection distance of about 3m). The latter is relevant for situations where the duration of the stimulus is longer than the time needed for the sound to travel from the source to the wall and back to the detection location, as is the case for typical hiss sounds and walls a couple of meters away.

We consider a situation of a detection location 12cm (45 pixels) away from the source center. The distance of 12 cm roughly corresponds to the distance between the mouth and the ears.
Interestingly, shortly after being launched, the initially monopolar Gaussian pressure wave packet evolves to a bipolar one. For the listening tests (see next section), we have removed the corresponding high pass filtering effect to a maximum extent by deconvolving the spectrum of the direct sound from the complete sound.

In listening tests, the spectra are affected by the temporal and spectral features of the emitted sound. However, in the following, for the sake of generality, we consider the response of the Gaussian source without convolution with a stimulus. In listening tests in an ideal anechoic environment, all surfaces except for the wall of interest are absorbing. In the simulated results, for the sake of simplicity we have not used perfectly matching layers, and considered rigid walls at the boundaries of the calculation domain. However, by putting a window around the signal parts of interest, the results are not affected by the respective reflections.

In the investigated case of a short pressure pulse (cfr. short mouth click) and wall at 1.5m distance, the direct sound and echo are temporally separated. The echo delay time is proportional to the wall distance, and information about the wall texture is fully contained in the spectral and temporal features of the short echo. Any variations made in the geometry of the object result in a temporal and spectral change of the reflected sound:

I.	Long (flat) wall	The acoustic reflection coefficient is essentially equal to unity, so the spectrum of the echo equals the spectrum of the direct sound.
II.	Short (flat) wall	In this case the reflection coefficient is affected by diffraction at the edges of the wall. The wall itself is 2.5m long.
III.	Wall with a hole	The magnitude of the echo is weaker, and there is a reduction of spectral energy and coloration due to frequency dependent diffraction by the hole. The hole has a width of 0.63m.
IV.	Staircase	In this case, with d=6.75cm the size of the steps of the stair, multiple echoes with intermediate time delays of $T=d/343 \approx 0.2$ms, occur, resulting in a spectral peak at a frequency of about 5000 Hz.
V.	Periodical wall	The modelled wall had a repetition length a, which leads to an angular interference spectrum with maxima for $\sin\theta = n\lambda/a$, with θ the angle with respect to the normal to the wall.

3.1 Signal spectra for different wall morphologies

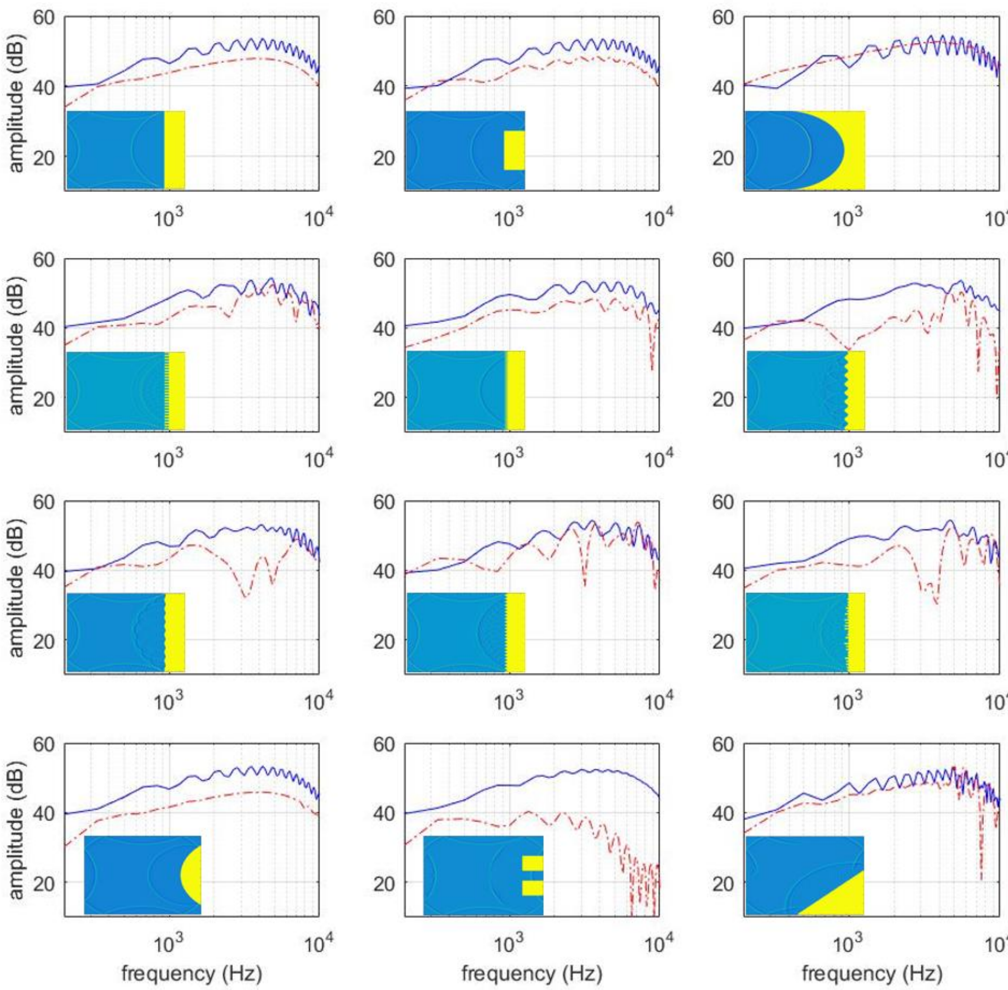

Figure 2. Overview of the different wall geometries, together with the spectrum of the reflected signal (red dashed line) and the spectrum of the reflected and direct signal (blue solid line).

3.1.1 Long wall

For the long wall, the reflection coefficient is essentially unity, so that the spectrum of the reflected echo is equal to the spectrum of the direct sound. The spectrum of the direct and echo sound together shows a comb filtering effect due to their distance and frequency dependent interference, with the modulation depth determined by their relative strength. In the considered 2D point source like situation, this is given by the distance ratio of roughly (12cm/3m)1/2 or -18dB, giving an interference contrast of 2010log(1+(12cm/3m)1/2)- 2010log(1+(12cm/3m)1/2)=3.5dB.

For the current investigation, in which we only consider temporally separated and thus subjectively perceived direct and echo sound, the spectrum of mixed direct and echo signal is not relevant, and will therefore not be reported for the other wall textures.

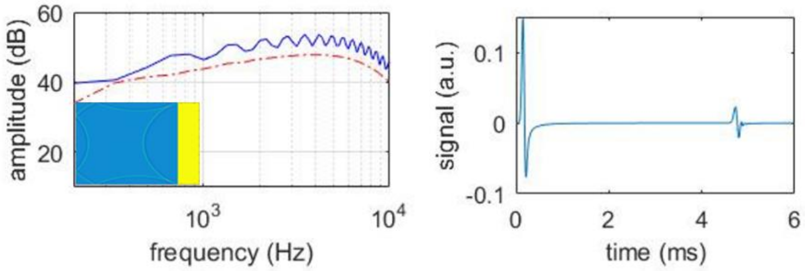

Figure 3. On the left the spectrum of the reflected signal (dashed red line) with the spectrum of the direct and reflected signal (blue solid line) in the case of a long (flat) wall at 150cm from the source. The right figure shows the time signal. The early bipolar wave packet in the time signal is the direct sound passing the measurement point, the late one is the echo.

3.1.2 Short wall

Compared to the spectrum of a long wall, due to diffraction, the spectrum of the short wall shows small periodical modulations, due the interference of waves originating from the wall ends that act like weak point sources, with the echo from the plane part of the wall. The amplitude depends on the phase difference between the interfering waves, which is given by $\Delta\phi = k\Delta s$, with $k=2\pi f/c$, the wave number, Δs the difference in travel distances and f the frequency.

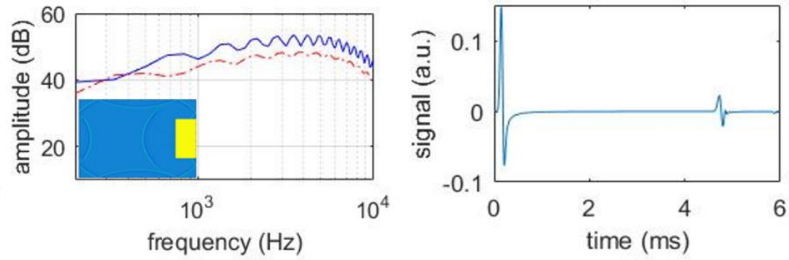

Figure 4. Left: spectrum of the reflected signal (dashed red line) and of the direct and reflected signal (blue solid line) in the case of a short (flat) wall at 150cm from the source. The wall has a width of 2.5m. The right figure shows the time signal.

3.1.3 Wall with a hole

The echo of the wall with a hole is overall slightly weaker in magnitude than the one of a plane wall. The spectral modulations are due to the frequency and distance dependent interference between waves from the edges of the hole with waves from the plane parts. The spectra corrugated wall echoes contain complex features due to frequency dependent scattering/diffraction of the incoming sound in other directions than the specular one.

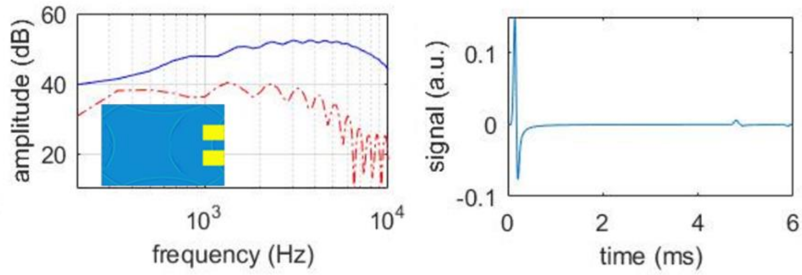

Figure 5. On the left the spectrum of the reflected signal (dashed red line) with the spectrum of the direct and reflected signal (blue solid line) in the case of a wall with a hole at 150cm from the source. The hole is 0.63m wide. The right figure shows the time signal. The weaker echo is clearly noticeable.

3.1.4 Staircase

In particular the staircase spectrum and signal are interesting. The periodic sequence of stairs at gradually increasing distance from the source results in a respective gradual arrival of individual echoes, with time intervals roughly given by $\Delta t_{stair} \cong 2d_{stair}/c$=0.4ms, with d_{stair} = 6.75cm the horizontal stair step width. Due to the increasing inclination of the source-stair step-receiver connection lines, Δt_{stair} is slightly changing as the echoes arrive from further distances. This chirp effect is well known, and was investigated in particular for the Chichen Itza pyramid in Mexico [2] [3]. For the considered staircase step width, the chirp frequencies lie around 2500 Hz.

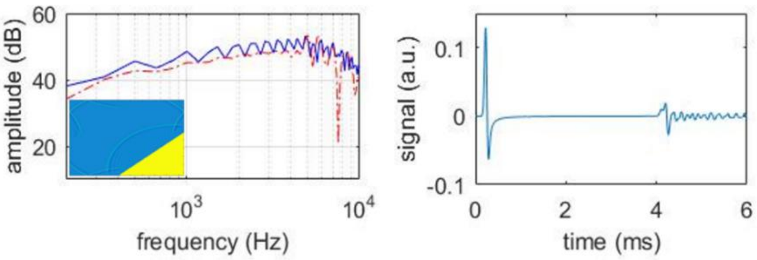

Figure 6. Left: spectrum of the reflected signal (dashed red line) and of the direct and reflected signal (blue solid line) in the case of a staircase at 150cm from the source. Each step is about 6.75cm high. Right: time signal.

3.1.5 Concave parabolic wall

Although the direct sound wave, generated by a small source, was not a plane wave, the parabolic shape of the wall somewhat leads to a modest focusing effect, resulting in an increased magnitude of the echo in comparison with the long flat wall (Figure 3).

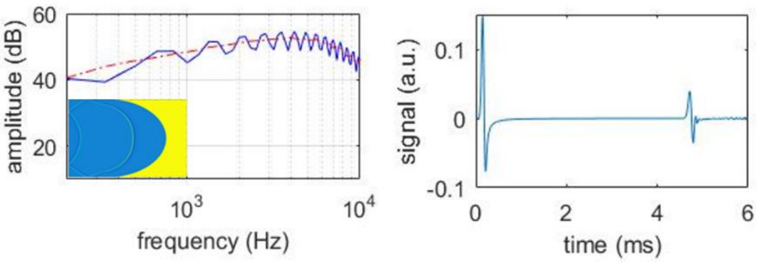

Figure 7. Left: spectrum of the reflected signal (dashed red line) and of the direct and reflected signal (blue solid line) in the case of a concave parabolical at 150cm from the source. Right: time signal.

4 Listening test results

Listening tests were performed in order to assess to what extent differences between sound reflections from walls with different morphologies are audible. Listening stimuli were based on simulated signals reported in sections 2 and 3. These were convolved with the stimulus of a “tongue click”.

Two sets of sounds were presented, respectively for the walls on a distance of 1000 mm and 150 mm from the source/listening position. For each set the test was based on a three-alternative forced choice (3AFC) without repetitions: the listening subjects were asked to determine whether the difference between two sounds affected by the presence of two different walls was small, obvious or not audible.

10 listening subjects participated in the experiments.

The listening tests were programmed in Excel and were made interactive, in a way that each test person was allowed to listen to the 2 stimuli as many times as wanted and was allowed to take a break anytime. In total 144 comparisons were performed per set.

The statistics of the answers reveal that the concave parabolic wall shape (wall 3) and the staircase (wall 11) were most easy to distinguish for a wall at 10 m distance. For the wall at 1.5m distance, the effect of the staircase reflection was the easiest to distinguish from other walls.

In general, differences between walls were easier detected for the wall at 10m distance than for the one at 1.5m distance.

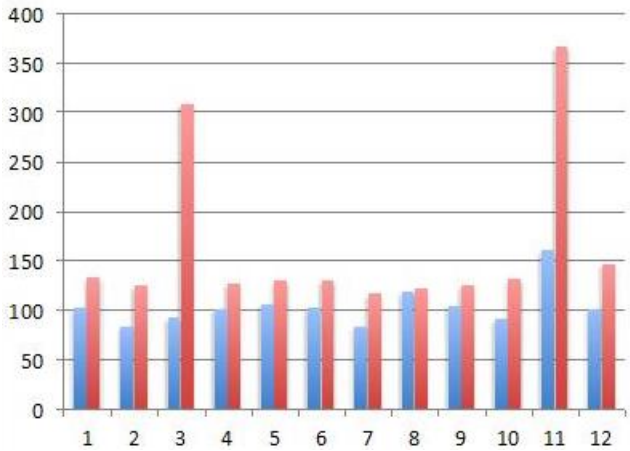

Figure 8. Statistics of the performed listening tests for the wall at 1.5m (blue) and 10m (red) distance. Surfaces 3 (parabolic wall shape) and 11 (staircase) were most distinguishable at a distance of 10m from the wall. The horizontal axis shows the data for respectively 1) circular wall, 2) short wall, 3) parabolic wall, 4) periodic square wave wall, 5), 6) and 7) variations 1,2 and 3 of a periodical wall, 8) periodical wall, 9) randomly blocked wall, 10) long wall, 11) staircase and 12) a wall with a hole.

5 Conclusion

The listening tests reveal that there is a noticeable (audible) difference between click sounds reflected off a regular, flat wall and an irregularly shaped wall like a staircase.

The difference in sound reflected from a concave parabolic wall, as shown in Figure 7, in comparison with the one reflected from other walls, was also very audible, due to the higher strength of the echo compared to other wall morphologies, especially at a large distance from the source.

The presence of a staircase was most audible in both the short distance as long distance case, due to the chirp effect mentioned in subsection 3.1.4.

For the wall at 1.5m the results reveal an audible difference between the four different periodical structures (bars 5,6,7 and 8 in Figure 8). The audibility was less for the case of the wall at 10m distance.

6 References

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